

ISSUES BEARING ON THE NEED FOR AND  
THE TIMING OF THE U.S. LIQUID METAL  
FAST BREEDER REACTOR

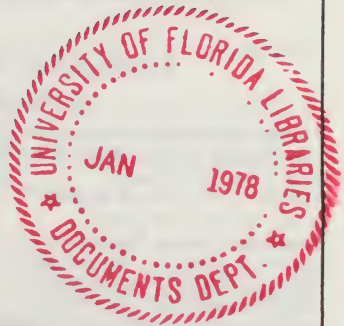
A REPORT PREPARED FOR  
THE SUBCOMMITTEE ON ENERGY AND  
THE ENVIRONMENT  
OF THE  
COMMITTEE ON  
INTERIOR AND INSULAR AFFAIRS  
OF THE  
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## LETTERS OF TRANSMITTAL

MAY 20, 1976.

MEMBERS OF THE COMMITTEE ON INTERIOR AND INSULAR AFFAIRS,  
*U.S. House of Representatives,*  
*Washington, D.C.*

DEAR COLLEAGUES: In recent months this committee's Subcommittee on Energy and the Environment has been concerned with the Nation's breeder reactor development program. At several of the subcommittee's hearings, testimony was received concerning the potential benefits and costs of the so-called breeder reactor.

Breeder reactors can utilize the bulk of uranium which occurs in nature in contrast to the relatively small fraction which can be used in fueling existing nuclear-generating stations. The Nation's reserves of nuclear fuel can be expanded nearly 50 times, according to the study, if breeder reactors can be demonstrated to be safe and economical.

Owing to the significance of this issue, I am forwarding to you the enclosed report, based in part on the subcommittee's hearings. This report, "Issues Bearing on the Need for and the Timing of the U.S. Liquid Metal Fast Breeder Reactor," was prepared by Frank von Hippel, a consultant to the subcommittee.

Sincerely,

JAMES A. HALEY,  
*Chairman.*

MAY 13, 1976.

HON. JAMES A. HALEY,  
*Chairman, Committee on Interior and Insular Affairs, U.S. House of Representatives, Washington, D.C.*

DEAR MR. CHAIRMAN: Transmitted herewith is a study entitled "Issues Bearing on the Need for and the Timing of the U.S. Liquid Metal Fast Breeder Reactor," prepared by Dr. Frank von Hippel, a special consultant to the Subcommittee on Energy and the Environment.

Dr. von Hippel's analysis provides information vital to an understanding of the Nation's breeder reactor development program. The study suggests that we are making a commitment to the liquid metal fast breeder reactor technology prior to the need for such a commitment and prior to our having information which will better tell us the precise direction in which we should proceed.

The analysis concludes that there are programs which would better serve the Nation's interest than the one on which we are now embarked. In particular, the study indicates that insufficient effort is being accorded uranium-conserving technologies which are more developed than the LMFBFR technology. Exploitation of these technologies would stretch our available uranium reserves while research

moves ahead on several fronts, thereby allowing a more deliberate consideration of the alternatives.

I believe this study demonstrates that the breeder reactor program must receive continuing scrutiny by this and other committees of Congress in order to insure that future decisions concerning breeder reactors are based on more comprehensive analysis of the alternatives than were the decisions leading to our present situation.

Sincerely,

MORRIS K. UDALL,  
*Chairman,*

*Subcommittee on Energy and the Environment.*

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## ISSUES BEARING ON THE NEED FOR AND THE TIMING OF THE U.S. LIQUID METAL FAST BREEDER REACTOR

### OVERVIEW

Current U.S. light water cooled reactors (LWR's) can release only about 1 percent of the energy stored in uranium. At this level of utilization, known U.S. reserves of high-grade uranium ore represent an energy resource no greater than U.S. reserves of oil or natural gas and are only a few percent as large as U.S. coal resources.

Despite this limited resource base, the Atomic Energy Commission and its successor agency, the Energy Research and Development Administration have projected for the year 2000 a nuclear-electric industry two to four times larger (in terms of power produced) than the total U.S. electrical utility industry in 1975.

If this power were produced by LWR's, currently estimated U.S. resources of high-grade uranium ore would be exhausted in a matter of decades. The AEC and ERDA have therefore made their number one energy R. & D. priority the development of a "breeder" reactor which would almost fully exploit the energy content of uranium. Virtually all the attention—both in the United States and abroad—has been focused on one breeder concept, the liquid metal-cooled fast breeder reactor (LMFBR).

Both the need for and desirability of the breeder are currently under hot debate:

With regard to the need, the proponents argue that uranium (as exploited by the LMFBR) and coal are the only two energy sources which can supply significantly increased amounts of energy for the U.S. economy by the year 2000. They believe that both of these resources must be exploited vigorously to compensate for dwindling U.S. production of oil and natural gas and to accommodate anticipated growth in energy consumption. The opponents respond that increased efficiency in the use of energy can make a massive buildup of nuclear power unnecessary in the short term and that solar energy would be a benign alternative to the LMFBR in the longer term.

With regard to the desirability, the opponents emphasize the fact that the LMFBR would commit the United States (and the world) to a "plutonium economy." They fear that the large-scale processing of plutonium which would be associated with the LMFBR technology would result in unacceptable levels of contamination of the environment by this manmade element, in thefts of plutonium by terrorist groups intent on making "homemade" nuclear bombs, and to a more rapid spread of nuclear weapons capability to currently nonnuclear nations. The proponents believe that the problems of keeping plutonium out of the environment and out of the hands of terrorists are manageable and that the

introduction of LMFBR technology would not significantly exacerbate the proliferation problem.

To some extent the debate over the breeder has merged with the larger debate over the need and desirability of fission power generally. To the extent that a vigorous breeder development program is symbolic of a long-term national commitment to fission energy, this connection may be legitimate. In the shorter term, however, the connection is not so close: There may be reasons for delaying a final decision on the breeder even if the hazards associated with current commercial nuclear reactors are found to be acceptable.

The principal focus of concern specific to the LMFBR stems from the fact that plutonium recycle is essential for the breeder whereas it is a relatively marginal proposition for LWR's.

The "plutonium economy" is so tightly connected with the breeder technology because the LMFBR exploits the 99 percent of uranium which current reactors do not by transmuting ("breeding") it into the chain reacting element plutonium, most of which must be recycled before it is consumed. LWR's produce some plutonium but not enough that recycling it will result in large increases in the efficiency of uranium utilization.

Much of the uncertainty associated with the debate over the LMFBR stems from the fact that, in the past, while much attention was being devoted to solving the difficult technical problems of design, too little attention was being devoted to the "soft" questions which require an assessment of the performance of human beings and their institutions:

Will the introduction of a U.S. civilian nuclear industry based on a "plutonium economy" significantly speed the spread of nuclear weapons to more countries?

Would a U.S. plutonium industry be well enough guarded to prevent nongovernmental groups from stealing plutonium and manufacturing their own nuclear weapons for purposes of blackmail or terrorism?

Would a U.S. plutonium industry be well enough managed and regulated to keep the "leakage" of plutonium and other long-lived radioactive materials into the environment down to tolerable level?

As a result of the current debate, these questions are now receiving serious attention but, at the best, it will be some time, probably years, before there will be anything approaching a consensus concerning the answers—either in the technical or in the larger political community.

In the meantime it would appear to be wise to postpone for a number of years final decisions about implementing the plutonium economy commercially—with either current LWR's or with breeders.

Revised estimates of future U.S. energy demand make this judgment easier. Past projections implicitly assumed that the real price of energy would continue to decline as it did during the 1950's and 1960's. In fact, however, the dramatic increases of the past few years of both the price of powerplants and fuel have already increased the real price of energy well above the 1950 price levels and there is now every expectation that the real price increases will continue—although at a lower rate—for the indefinite future.

With these price rises it seems reasonable to expect growth rates in the demand for energy to decrease substantially as energy becomes more expensive and increased efficiency in the use of energy becomes worth investing in. Past official projections for the future growth of nuclear energy are therefore beginning to look increasingly questionable.

The most recent of the ERDA projections (spring 1975) had nuclear energy generating electric power at an average rate of 440 million to 880 million kilowatts by the year 2000—which is to be compared with the approximately 200 million kilowatts generated by the entire electrical utility industry in 1975. To obtain this enormous growth rate, ERDA made the following assumptions: (a) Total U.S. energy consumption would increase by between 80 to 160 percent by the year 2000, (b) The fraction of U.S. fuel devoted to the production of electrical energy would approximately double (from about 25 percent to over 50 percent), and (c) Nuclear-electric powerplants would generate between 55 and 76 percent of all electric power consumed in 2000 (up from approximately 10 percent in 1975).

Are these projections realistic? There appears to be an increasing consensus both inside and outside ERDA that they are not. Even if the utilities were able to obtain the necessary trillion or so dollars of capital, the nuclear industry were able to bring the plants into operation at the necessary rate of 150 plants a year by the year 2000, and it was possible to obtain acceptable sites for all of these powerplants, there would still be the question as to who would buy all that power at the new high prices. Even if the electrical share of the energy market continues to expand, the slowed growth rate of total energy consumption will result in a slower growth for electrical energy. This will in turn bring about a decreased rate of construction of new nuclear-electric capacity—a trend which is already well begun. It seems likely that even the low end of ERDA's range of estimated year 2000 nuclear capacity will turn out to be high—and in fact, an informal inquiry at ERDA revealed that the projection which the agency described as "moderate/low" a year ago is now labeled "high."

Lower growth rates of electrical consumption would save the United States from any imminent danger of running out of high-grade uranium ore. Currently ERDA estimates U.S. reserves and probable resources of uranium at about  $11\frac{1}{2}$  million tons—enough to fuel approximately 360 million kilowatts of nuclear power for 30 years (the estimated lifetime of a nuclear plant). This corresponds at a 65 percent average capacity factor for a nuclear generating capacity of 550 million kilowatts. It seems highly unlikely now that U.S. nuclear capacity will exceed this value by the year 2000. By that time it is likely also that additional uranium resources will have been identified and that the nuclear fuel cycle can have been made as much as twice as efficient as today in its use of uranium without plutonium recycle. There seems therefore to be no reason to rush the decision to go ahead with the LMFBFR—or with any other version of the plutonium economy.

From this perspective it appears that the almost exclusive emphasis on the LMFBFR in the Nation's R. & D. program over the past decade has been unfortunate. It has given us an energy option which may or

may not be exploited some decades hence, but it has left us with too few options to be exploited during the next decades.

In view of the uncertain political future of fission, it is important now to develop such alternative energy options. The objective of the Nation's energy R. & D. program in these changing times should be diversity and flexibility. From this perspective it is encouraging to see ERDA's activities increasing in the areas of energy conservation and solar energy. These efforts are still relatively small and tentative, however, in comparison to the LMFBR program and the emphasis in the President's fiscal 1977 budget remains on fission: In this budget \$839 million authorization is requested for fission (mostly LMFBR related) which is to be compared with \$120 million for energy conservation and \$160 million for solar energy. The increases over the previous budget authorization are: \$45 million for energy conservation, \$45 million for solar energy, and \$224 million for fission. Obviously funds should not be channeled into solar and energy conservation research and development projects more rapidly than they can be effectively utilized. Projects with major potential payoffs are being identified in these areas, however and, unless available energy R. & D. funds are channeled preferentially into those areas, there appears to be a real danger that the lion's share of funding increases will be absorbed by the continual cost overruns of the LMFBR program.

If flexibility and diversity are required in the Nation's overall energy R. & D. program they are also important within the fission R. & D. program itself. Unfortunately the trend here seems to be in the opposite direction. Virtually the entire fission R. & D. effort is now devoted to solving the problems of the LMFBR and LWR technologies. The snowballing budget is not evidence of new initiatives, rather it reflects mainly tremendous cost overruns and efforts to deal with proliferating safety issues without making any basic changes in the reactor designs. In fact, in the future annals of fission R. & D., fiscal 1976 is likely to be remembered less for the results of the half a billion dollars invested in LMFBR technology than for the virtual termination of R. & D. on two reactor designs based on the "thorium economy" which offered an alternative to the "plutonium economy." It is not certain at this time that a fission fuel cycle based on thorium would ultimately prove to be more benign than one based on the plutonium breeder. It is certain, however, that many of the problems would be quite different. At a time when the concept of a plutonium economy is under such vigorous attack, one would think that interest in thorium-based reactors would increase. Instead the commercial developer of the high-temperature gas-cooled reactor went out of the business for lack of Federal interest and the budget for work on the Molten Salt Breeder Reactor was cut from \$4 million in fiscal 1976 to zero in the administration's proposed budget for 1977.

The purpose of the report which follows is to provide to Congress additional background on the principal issues in the LMFBR debate.

## I. THE RATIONALE FOR THE BREEDER REACTOR

In the winter of 1973-74 the oil exporting nations demonstrated dramatically that control over the international oil market had shifted from the consumers to the suppliers. The price of international oil rose several fold putting a serious strain on the economies of the oil importing nations. Perhaps as important was the discovery by the major oil exporting nations of the Middle East of the political leverage inherent in their control over the fuel supplies of the oil importing nations. In the United States and in many other nations increased "energy independence" became a national policy goal.

Since that time it has become apparent, however, that increasing the domestic supplies of energy will not be an easy task. In the United States the production of both oil and natural gas have begun to decline and current estimates of recoverable U.S. resources of these fuels indicate that it is unlikely that they can continue to supply the bulk of U.S. energy beyond the year 2000.

The resource situation for coal is much more favorable but there are very serious environmental and occupational health problems currently associated with both coal mining and coal burning. Even greater environmental problems can be expected with the exploitation of the other major U.S. fossil fuel resource, oil shale.

An additional concern which applies to the use of all fossil fuels stems from the fact that about one half of the carbon dioxide produced by their combustion in the past has accumulated in the atmosphere. Some climatologists are concerned that a continued buildup in atmospheric  $\text{CO}_2$  may result within decades in changes in the Earth's climate large enough to have a major impact on world agriculture. [1]

The stage therefore appears to be set for the introduction into the U.S. energy supply of one or more major new energy sources not dependent on fossil fuels. Currently the prime candidates are the fission of heavy atoms, sunlight, and the fusion of light atoms.

In the past decades the greatest priority in U.S. energy research and development has been accorded to the development of economical fission power. Recently, however, the energy crisis and controversy concerning the safety, and environmental hazards associated with fission energy have led to a dramatic increase in the levels of funding devoted to solar and fusion energy. It will be several years, however, in the case of solar energy and perhaps decades in the case of fusion, before their potentials and limitations are as well established as are those of fission energy. It would therefore appear to be premature to foreclose the future of fission energy before the policy issues relating to the alternatives become more clearly defined.

It is in this context then that we confront the issues posed by the proposed liquid metal cooled fast breeder reactor (LMFBR).

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NOTE.—All footnotes to the text appear at the end of the report and begin on p. 21.

The development of the breeder reactor is being proposed because current U.S. water cooled reactors are able to release only about 1 percent of the stored energy in natural uranium. An LMFBR would make possible the release of over 50 percent. (See app. A.)

The factor of 50 or so increase in the extraction of energy from uranium is important because high-grade uranium ore is much less abundant than high grade fossil fuel deposits in the Earth's crust. Estimates of the U.S. economically recoverable coal resources, for example are of the order of 1 trillion tons [2]—enough to support U.S. energy consumption at the current rate for about 300 years. U.S. resources of high-grade uranium ore are estimated to be of the order of millions of tons.[3] A million tons of uranium is equivalent to approximately 2 trillion tons of coal if used to fuel a breeder reactor but it is only equivalent to about 40 billion tons of coal if used in current commercial nuclear reactors. With current technology, therefore, high-grade uranium ore represents a rather small energy resource relative to coal. With a breeder reactor the uranium resource would grow in two ways: The releasable energy in a pound of uranium ore would be increased by a factor of 50 or so, as has already been noted, and it would become economic to mine much lower grades of uranium ore—even to extract dissolved uranium from ocean water. Uranium—and thorium—would then come to represent very large energy resources indeed in comparison to the fossil fuels.

## II. HAZARDS OF A PLUTONIUM ECONOMY

While the LMFBR would remove the short-term resource limitations on fission energy, it would also tend to exacerbate some of the troublesome problems of our current fission power technology. In particular, it would require the introduction of a "plutonium economy."

Plutonium is produced by conventional water-cooled reactors just as it is by the LMFBR. The LMFBR technology requires recycle of the produced plutonium, however, while the water-cooled reactors do not. Recycle of the produced plutonium and the leftover uranium-235 in the spent fuel from a conventional water-cooled reactor increases the amount of energy extracted from the original uranium ore by less than 50 percent [4] and it is a marginal decision whether the fuel value of the recovered uranium and plutonium justifies the cost of the reprocessing of the fuel. [5] In contrast, the LMFBR technology is premised on the chemical purification and recycling of the fuel tens of times before all the uranium has been converted into plutonium and fissioned.[6]

The plutonium economy raises two types of concerns:\*

### 1. ENVIRONMENTAL

Plutonium is an extremely hazardous and long-lived environmental contaminant. The more that it is handled, the larger the fraction which

\*Perhaps the most sustained effort to bring these concerns to public attention has been made by the Natural Resources Defense Council (beginning with the lawsuit which resulted in the AEC's "LMFBR Program Environment Impact Statement"), and with critiques of that program growing out of Dr. Thomas Cochran's book, "The Liquid Metal Fast Breeder Reactor: An Environmental and Economic Critique" (Resources for the Future, 1974).

will tend to find its way into the environment. ERDA has set as an objective the containment of plutonium and the associated long-lived radioactive isotopes at a level where only one atom out of a billion processed in the LMFBR fuel cycle will leak out into the environment.[7] Various groups including the EPA have raised questions as to whether such an objective is achievable in practice. If it is not, then we must face the question on whether achievable containment levels are tolerable. (See app. B.)

## 2. DIVERSION

It takes a rather elaborate facility to separate plutonium from the highly radioactive fission products. Once this has been done, however, the plutonium is easy enough to handle so that there is legitimate concern that a small group of individuals with rather modest resources might be able to steal some of the material and fabricate a crude nuclear weapon.[8] Less than 20 pounds of plutonium would be required for the manufacture of a crude nuclear explosive with an expected yield equivalent to more than 100 tons of TNT. By the year 2000 approximately 20,000 times this much new plutonium would be produced each year in the projected fission economy of about 1,000 large 1 million kilowatt reactors.[9] (See app. C.)

On the international level, the prospect of a plutonium economy raises the issue of a proliferation of nuclear weapons states based on plutonium separated out from the spent fuel of nuclear powerplants. Establishing the plutonium economy as an integral part of nuclear energy technology could be a significant step in facilitating the promotion of other nations with nuclear powerplants to the nuclear weapons "club."

Aside from the issues posed by the plutonium economy, the LMFBR seems to have both safety advantages and disadvantages when compared with current water-cooled reactors. It is unclear at the present time therefore which design is safer. (See app. D.)

## III. TIMING OF THE LMFBR DECISION

The timing of the decision in the United States on whether or not to go ahead with the breeder reactor depends in part on the larger energy policy context discussed above, that is, on a continuing comparison of the relative promise and hazards of the alternative energy supply technologies.

The decision to go ahead with the LMFBR or some other uranium conserving reactor design will depend also upon the rate at which the U.S. resources of high-grade uranium ore are depleted.\* This rate of depletion in turn depends on two factors: (1) The rate at which U.S. reactors consume uranium, (2) the total U.S. resources of high-grade uranium ore.

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\*For the present purposes we will ignore the possibility of the United States importing (or exporting) significant amounts of uranium. According to current estimates the United States possesses approximately one-third of the world's high-grade uranium resources outside the Communist bloc. (Testimony of Robert Nininger, "Oversight Hearings on Nuclear Energy—Part II," June 5, 1975, p. 403.) This may merely reflect, however, the relatively advanced state of exploration in the United States.

## 1. RATE OF CONSUMPTION OF URANIUM

Essentially all currently operating U.S. commercial nuclear power reactors are light water-cooled reactors—LWR's.\*† As of June 30, 1975, the total U.S. nuclear generating capacity totaled less than 37,000 megawatts electric (MWe). Additional capacity totaling 77,000 MWe was under construction, however and a further 104,000 MWe of capacity was on order for a grand total of 218,000 MWe. [10] The total U.S. electrical generating capacity as of the end of 1975 was about 492,000 megawatts. [11] The nuclear capacity built, under construction or on order is therefore equivalent to almost one half of the Nation's fossil fueled generating capacity.

A 1,000 megawatt electric (MWe) light water-cooled reactor—the most common U.S. power reactor—currently requires about 165 tons of unenriched uranium oxide ( $U_3O_8$ ) per year. [12] By increasing the extraction of uranium-235 out of the natural uranium at the enrichment plant back to past levels, this requirement could be reduced by approximately 16 percent. [13] With recycle of uranium it could be reduced by a further 17 percent and a final 17-percent reduction could be obtained by recycling the produced plutonium for a total potential saving of approximately 40 percent. [4] For the approximately 200,000 MWe of capacity currently built, under construction, or on order, operating for a 30-year lifetime, the  $U_3O_8$  requirements in the absence of any of these changes would be approximately 1.2 million tons. [14] With all of the changes, the requirements could be reduced to approximately 700,000 tons.

In testimony before the subcommittee, Roger Legassie, ERDA's Assistant Administrator for Planning and Analysis, presented a projection of nuclear capacity for the year 2000 as between 625,000 and 1,250,000 MWe. This nuclear capacity was assumed to generate between 50 and 75 percent of the total electrical energy consumed in that year which was assumed in turn to account for approximately 50 percent of all fuel energy consumed in that year—compared with approximately 26 percent currently. The total U.S. energy budget in the year 2000 was assumed to be between 1.8 and 2.6 times larger than the 1973 U.S. energy budget. [15] Similar electrical energy growth projections were offered to the committee by Robert Smith, president of Public Service Electric and Gas of New Jersey and chairman of the Energy Analysis Division Executive Committee of the Edison Electric Institute. [16] The range of year 2000 nuclear energy capacity projections offered the subcommittee in testimony by John Hill, Deputy Administrator of the Federal Energy Administration, 600,000 to 700,000 megawatts, fell at the low end of ERDA's range of projections but still represented an enormous growth. [17]

If such growth were realized and if new uranium conserving nuclear reactor designs were not introduced, then the 30-year uranium requirements for U.S. reactors operating in the year 2000 would be increased threefold to sixfold beyond the requirements for the capacity already under construction, being built, or on order.

\*The cooling water is termed "light" to distinguish it from the "heavy water" used in Canadian type power reactors. In heavy water "heavy hydrogen" or deuterium atoms are substituted for the ordinary hydrogen atoms in  $H_2O$ . Heavy water is expensive but has the advantage of capturing fewer neutrons than are captured in light water.

†One small 330 million watt High Temperature Gas Cooled Reactor (HTGR) has just been put into operation in Colorado.<sup>10</sup>

Quite a different perspective on electrical energy growth projections was offered to the subcommittee by Professors Duane Chapman and Timothy Mount of Cornell University.[18] Professors Chapman and Mount pointed out that the past rapid increases in demand for electrical energy—an approximate doubling every 10 years since 1920 [19]—were accompanied by corresponding dramatic decreases in the cost of electric power relative to the costs of other commodities.

Between 1950 and 1970 this relative cost fell by a factor of two.[20]\* In their testimony they pointed out that this trend of declining real prices of electricity has now been reversed with a 50-percent increase in the relative prices of electricity from 1972 to 1974. With these price increases they expect a dramatic slowing in the growth rate of electric energy demand.

Another witness Dr. Robert Williams, then director of research of the Institute for Public Policy Alternatives of the State University of New York, and formerly senior scientist at the Ford Foundation's energy policy project directed the subcommittee's attention [21] to a study done for the Ford Foundation's energy policy project (EPP) by Edward A. Hudson and Dale W. Jorgenson of Data Resources Inc. (DRI).[22] The findings of this study appeared to support the contentions of Chapman and Mount.

The DRI study uses an approximate mathematical description of the U.S. economy to estimate the effects of price increases in electrical and other forms of energy on the rest of the economy. The economists used their model to determine what changes in energy prices and Government policies would be required for energy consumption to continue to grow at the historical rate—or to grow at specified lower rates. They found that a continuation of the dramatic relative price decreases of the past would have to occur for electricity to realize growth rates in demand such as those projected by the Government and the utilities, that is, the relative price of electricity would have to drop by 50 percent to bring about the fourfold increase in electrical demand by the year 2000 that ERDA characterized as “moderate to low.” On the other hand, with a rather modest 30-percent increase in the relative price of electricity, it was found that the consumption of electricity would only double by the year 2000.

Quite encouragingly the DRI study found that such very different projections in the relative prices of and demand for electricity had little effect on the growth of employment or of the economy. The higher prices had primarily the effect of stimulating increased efficiency in the use of energy in the satisfaction of essentially the same final consumer demands. Quantitatively the DRI analysis showed a slightly reduced GNP (4 percent subtracted from a real growth of 130 percent) in the year 2000 in this “technical fix” scenario but a slightly increased employment (3 percent added to a growth of 50 percent in man-hours.) The increased employment stemmed from the fact that energy-conserving production procedures will tend to be slightly more labor intensive.

Dr. Williams also submitted for the record a paper published by John G. Myers of the Conference Board. [23] This paper points out

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\*In this connection it is interesting to note that, although the consumption of electricity grew much more rapidly than the gross national product (measured in constant dollars) between 1950 and 1970 (5 times compared to 2 times), due to the relative price decrease of electricity, the share of the gross national product being expended on the purchase of electric energy increased only slowly—by approximately 25 percent over the same period.

that, despite a decrease of 24 percent in the price of energy relative to other commodities between 1947 and 1970, the average rate of growth in energy consumption over the same period was approximately 0.6 percent slower than the average rate of (real) growth of the gross national product. With the recent increase in energy prices Mr. Myers suggested that the difference between these two growth rates might open up to 2 percent, that is, that only about a  $11\frac{1}{2}$  percent energy consumption growth rate would be required to support a growth rate of  $3\frac{1}{2}$  percent in the real GNP.

To substantiate the DRI assertion that it would be possible to increase the real GNP by 130 percent while increasing total energy consumption by only approximately 50 percent (that is, to increase the ratio of real GNP to total energy consumed by 50 percent), Dr. Williams offered a detailed list of currently feasible and economically justified measures for increasing dramatically the efficiency of our current use of energy. He stated that, if these measures were adopted throughout the economy, the amount of energy required to produce an average unit of the gross national product could be reduced by approximately 40 percent.

Of course, in view of the peaking of U.S. production of our principal fuels, oil and natural gas (currently about 75 percent of U.S. energy supply), one can expect a continued shift of the Nation's economy to electric energy derived from coal and uranium fueled powerplants. Even if the electric sector were to grow to the point where it consumed 50 percent of the total primary fuel used by the economy (up from 26 percent in 1973), however, the average growth rate of the electrical energy sector would be less than 3 percent greater than that of total energy consumption—approximately the historical difference. A reduced growth rate in overall energy consumption would therefore be reflected in a reduced growth rate in electrical energy consumption.

It appears that the analysis presented by Chapman, Mount, and Williams call into substantial question the administration's projections of electrical energy growth.

## 2. U.S. URANIUM RESOURCES

The subcommittee heard testimony on the uranium resource situation from Mr. Robert Nininger, ERDA's Assistant Director for Raw Materials. [24] Mr. Nininger testified that, as of January 1, 1975, ERDA estimated that the United States had in well-established reserves approximately 690,000 tons of  $U_3O_8$ —mostly in uranium ore of a grade comparable with that currently being mined. (Included was 90,000 tons classed as being recoverable as a byproduct from phosphate or copper mining by the year 2000). Mr. Nininger also presented ERDA estimates that an additional "potential resource" of approximately 2.9 million tons of  $U_3O_8$  in ores of similar grade was still to be found for a grand total estimated resource base of 3.6 million tons  $U_3O_8$  in "high grade" ores. These "high grade" ores currently being mined average approximately 0.2 percent uranium by weight. [25] The ore which Mr. Nininger included in his estimate went down to approximately 0.06 percent uranium by weight. [26] \*

\*Although in a percentage sense this ore appears quite low grade, in an energy sense it is not. Even at 0.1 percent uranium by weight, 1 ton of uranium ore can provide the equivalent energy of 20 tons of coal when used to fuel a water-cooled reactor and the equivalent to 1,000 tons of coal when used to fuel a breeder reactor.

If the United States exhausts its high-grade uranium resources, then it will have to turn to lower grade resources. ERDA's current information is that the United States has no significant uranium resources in ores between 0.07 and 0.008 percent uranium by weight. The next major resource is in Chattanooga shale which is estimated by ERDA to contain approximately 13 million tons of  $U_3O_8$  at a concentration ranging from 0.0080 to 0.0025 percent. [27] At 0.0050 percent the uranium in a ton of ore would have about the same energy value as fuel for a U.S. water-cooled reactor as a ton of coal for a coal-fueled powerplant. ERDA believes that most of the mining would have to be done underground. Current underground coal mining would fuel only approximately 125,000 megawatts of coal powerplant capacity at a 65-percent capacity factor. Approximately 100,000 equivalent full-time miners work to provide this coal. [28] Supporting a nuclear energy capacity of several hundred thousand megawatts by mining Chattanooga shale does not therefore appear to be an attractive prospect.

The subcommittee also heard from Mr. Milton Searl who had a much more optimistic view than ERDA of the U.S. potential uranium resources. [29] Mr. Searl, manager of the energy supply studies program of the electric utilities' Electric Power Research Institute, expressed his belief that ERDA's current estimates of uranium resources in high-grade uranium ore will prove to be low for two principal reasons:

1. ERDA's resource estimates are dominated by ore deposits at relatively shallow depths. Mr. Searl suggested that this shallow distribution was not a result of the actual distribution of deposits with depth but instead simply reflected the fact that shallower deposits are easier to find. As support for this contention Mr. Searl noted that the average depth of ERDA's \$8 per pound  $U_3O_8$  cost category of uranium reserves was approximately 400 feet in 1973—quite close to the average depth of exploratory drilling over the previous several years. [30] Searl pointed out that, if uranium ore were indeed distributed uniformly with depth down to say 4,000 feet, then the sum of ERDA's resource figure plus past production (assuming that it also was at an average depth of 400 feet) should be multiplied by approximately a factor of 5 to obtain a corrected estimate for resources. He noted, however, that the deeper uranium ore would be both more difficult to find and more costly to mine.

2. Not only is the exploration of the country at depth incomplete, it is also far from complete over the area of the United States. Mr. Searl testified that: "A review of the literature convinced us that the total prospective area in the United States potentially productive was 30 times the known producing area." Assuming that no areas with larger reserves remained to be discovered, he estimated on the basis of experience with the distribution of other mineral resources that other districts with a total uranium resource approximately three times greater than that of the currently producing area would be found. [30]

Correcting the ERDA resource estimates for these two considerations would raise them by a factor of 20 to 72 million tons. In actual fact, in a document submitted for the record [30] Mr. Searl suggested, however, that the United States has a resources base of high-grade uranium ore in the range 13 to 29 million tons, for the entire United States. This estimate is not comparable to ERDA's current estimate,

however, since it was based on a 1973 ERDA estimate of certain classes of reserves totaling 1 million tons.

If Mr. Searl is correct, then there is much more high-grade uranium ore to be found in the United States beyond the 3 million tons of  $U_3O_8$  equivalent estimated by ERDA. This would be in keeping with history where ERDA's estimates in one category for which we have historical information (less than \$15 per pound  $U_3O_8$  forward costs\*) have increased from 570,000 tons [31] in 1967 to approximately 1 million tons [31] in the period 1969-73, to approximately 2 million tons [26] at the beginning of 1975.

Such arguments are not a sufficient basis for public policy, however, and it is important that the uncertainty in U.S. high-grade uranium resources be greatly reduced.

Since 1958 uranium exploration has been left to industry with the AEC—now ERDA—largely playing the bookkeeper's role. This was adequate when the required forward reserve was 8 to 10 years current production and production was averaging only about 12,000 tons of  $U_3O_8$  per year. [25] With the projected demand rising to 40,000 tons per year before 1985, and the breeder decision depending upon the adequacy of our uranium reserves to supply the lifetime requirements of reactors built in the year 2000, however, it will be necessary to make an effort to identify uranium resources which goes beyond that which is justified by the short-term planning requirements of the uranium mining industry itself.

In response to this obvious need, the AEC embarked in 1973 on its own national uranium resource evaluation (NURE) program funded at the level of \$7 million [32] for fiscal years 1974 and 1975. The result in the first 18 months' work has been an increase of 1.2 million tons in ERDA's  $U_3O_8$  resource estimate. [24] This first phase of the NURE program which was programed to be completed by January 1976 involves the assembly and analysis of existing information with experienced uranium geologists making estimates based on industry data, field examinations, available geologic reports, discussion with other Federal, State, and university geologists, as well as their own experience and judgment. Each geographic area is examined and judged on key geologic characteristics and compared with areas of known uranium reserves and ore controls. [24]

The second phase of the NURE program, which is to be completed by 1980, would involve ERDA developing new resource information through an aggressive program of geologic and geochemical investigations, geologic drilling and aerial and other geophysical surveys. [25] The NURE program would also include an effort to upgrade the exploration techniques of industry. The uranium industry expended approximately \$50 million on exploration efforts in 1973 and has been rapidly increasing its efforts since. [25] It appears obvious that this program should be pursued with the highest priority.

ERDA's uranium resource evaluation program should also be improved where possible. Mr. Searl suggested a number of possibilities for such improvements including:

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\*Forward costs are ERDA's estimated costs for mining, hauling, and milling of the ore plus royalties. It does not include "sunk costs," such as costs already expended in exploration and property acquisition nor does it include profits or interest. Due to inflation and sometimes the closing of mines, the more expensive ore in a particular forward cost category will tend to move into the next higher category. In order for resources to increase therefore, the rate of discovery of new resources must exceed the rate of mining plus attrition due to inflation and other effects.

1. An assessment of whether past exploration efforts ignored uranium deposits which were not then of economic interest but might be by the end of the century.\*

2. A systematic approach to understanding the distribution of uranium deposits as a function of depth, size, and grade.

3. Making ERDA's data bank on uranium resources more accessible to outside analysts who might be able to suggest improvements in ERDA's approach to the problem.

In view of the importance of the uranium resource question, it might be appropriate to convene a qualified review group—possibly under the auspices of the National Academy of Sciences—to review the NURE program. This review should assess the adequacy of the coverage of this program as well as the effectiveness with which it utilizes the expertise available in other Government agencies such as the U.S. Geological Survey and in universities. A considerably higher level of funding for the uranium resource assessment program could be justified if such funds could be effectively spent.

#### IV. OTHER URANIUM CONSERVING REACTORS

The discussion above has ignored the fact that there are more than the two types of nuclear reactors discussed so far: The standard U.S. light water cooled reactor (LWR) and the proposed liquid metal cooled fast breeder reactor (LMFBR). In fact, in addition to other proposed breeder reactor designs, there are at least two additional developed reactor types whose requirements for uranium per kilowatt hours of electricity generated would lie between those of the LWR and LMFBR. These reactors are the commercially successful Canadian heavy water reactor (CANDU) and the U.S. high-temperature gas-cooled reactor (HTGR) whose commercial future is currently in question. Use of these two reactor types would reduce the uranium requirements per kilowatt hour by a factor of approximately two with either a once through or a recycle fission economy. (See app. E.)

In practice, of course, there would be difficulties in substituting these reactors for LWR's in the U.S. reactor market. Neither the HTGR nor the CANDU has an obvious economic advantage over the light-water reactors with the uranium prices expected over the next decade or so and they have the disadvantage of competing with an established reactor type. In addition, even if the reluctance of the market could be overcome, it would take a considerable time before the industry could be geared up to produce either of these reactor types in quantities comparable to the numbers of light-water reactors currently being built. It should be noted, however, that both of these objections apply at least as strongly to the LMFBR.

#### 1. THE THORIUM ECONOMY AND "NEAR BREEDERS"

If a decision were made to go to a fuel recycle economy with any of the current generation of commercial power reactors, then the greatest conservation of uranium would be possible if the uranium<sup>235</sup> were separated from the uranium<sup>238</sup> which makes up the remaining 99.3 percent of natural uranium and were mixed with thorium instead.

\*One wonders in this connection whether it might not be possible to "piggyback" a great deal of uranium exploration on drilling efforts aimed at developing new oil and gas reserves.

In such an arrangement a new chain reacting element uranium <sup>233</sup> would be bred out of the thorium instead of the plutonium which is bred out of uranium <sup>238</sup>. For the LWR, HTGR, and CANDU which all use slowed down neutrons in their chain reactions, conversion in the thorium-uranium fuel cycle would be somewhat more efficient than in the uranium-plutonium fuel cycle. The opposite is true for the LMFBR which uses fast neutrons in the chain reaction.

One advantage of the uranium-thorium fuel cycle is that use of it would allow an evolutionary development of current reactor designs toward designs which would use uranium more and more efficiently. Thus both the HTGR and the CANDU could probably be upgraded to at least near-breeder status. [33] In fact ERDA is currently funding what is intrinsically a more difficult development project: the upgrading of the Shippingport light water cooled reactor to the status of a breakeven breeder reactor—a reactor which utilizes uranium as efficiently as the proposed LMFBR but unlike the LMFBR does not breed significant amounts of surplus fissionable material to fuel new reactors. [33]

With ERDA's projected growth rate for the U.S. nuclear power capacity and its estimates of U.S. uranium reserves, it would probably be impossible to introduce HTGR's or CANDU's rapidly enough to prevent a severe uranium shortage with the LMFBR. In fact in the short term uranium supply and enrichment capacity problem might be exacerbated by the introduction of uranium conserving reactors since many designs have greater initial fuel requirements than conventional reactors although their requirements for makeup fuel are less. In such designs it might be a decade after initial operation before the net savings began to accrue. [33] If the nuclear power growth rate turns out to be significantly slower or U.S. uranium resources are found to be significantly larger, however, then this option might prove to be quite attractive. An added incentive for exploring it is provided by the fact that the uranium-thorium fuel cycle might have advantages over the uranium-plutonium fuel cycle with respect to environmental contamination and/or safeguards against diversion of fuel materials to use in nuclear explosives.

## 2. OTHER BREEDER REACTORS

In addition to the LMFBR two other breeder reactor concepts have been seriously put forward by U.S. nuclear energy technologists: the molten salt breeder reactor (MSBR) and the gas cooled fast breeder reactor (GFBR).

*Molten Salt Breeder Reactor (MSBR).*—The molten salt breeder reactor is a concept which has been developed and embodied in a small test reactor at Oak Ridge National Laboratory. It is a reactor which operates on a thorium fuel cycle with thermal neutrons. It is promoted from a near breeder to breeder status by having its fuel in molten form mixed with the coolant. This makes it possible to purify and recycle the fuel continuously thereby keeping neutron capturing impurities at a lower level than would be feasible with a solid fueled reactor. Over the past several years the MSBR development program has been maintained at a level sufficient to conduct research and development on key technical problems and retain the MSBR concept as

a potential backup to solid fuel breeder reactors. [34] In the administration's proposed fiscal 1977 budget no funds are included for the continuation of the development of the MSBR.

*Gas Cooled Fast Breeder Reactor.*—This is a concept developed principally by the General Atomics Co. with some utility and Federal support. The idea is to combine the helium coolant and prestressed concrete pressure vessel technology developed by General Atomics for the HTGR with the LMFBR fuel technology being developed by ERDA. The helium coolant of the GFR would interfere less with the passage of neutrons from fuel rod to fuel rod in the reactor core than would the liquid sodium coolant in the LMFBR. As a result the GFR would have a somewhat higher breeding ratio. The GFR would have the safety disadvantage, however, that its coolant would be under high pressure and would consequently be expelled in case of a rupture in the pressure vessel.

Currently the LMFBR concept is receiving the overwhelming percentage of breeder reactor development funding, both in the United States and elsewhere. Some experts have suggested that it may prove to be a false economy not to have developed more aggressively an alternative breeder concept if the LMFBR development program produces a reactor which is either not sufficiently safe or economic or if the plutonium economy proves to be unacceptable for either environmental or safeguards reasons. In such a case a thermal breeder reactor or near breeder based on the thorium economy would differ in enough respects from the LMFBR so that it might not encounter the same objections.

## V. ECONOMICS

A breeder system reactor would only require about 2 percent as much uranium to be mined as a light-water reactor per kilowatt-hour of energy generated. The fact that this would stretch U.S. uranium resources has already been mentioned. It would also be an economic advantage, however, which would increase as high-grade uranium ores became depleted and the price of uranium increased.

On the other hand, the capital costs for LMFBR's would probably be higher than those of a light-water reactor. (See app. F.) Dr. John J. Taylor, then vice president and general manager for Advanced Nuclear Energy Systems at the Westinghouse Electric Corp., the prime contractor for the Clinch River LMFBR demonstrator reactor told the subcommittee on June 6, 1975, that he believed that a commercial LMFBR in 1990 would have a plant capital cost than a water reactor of equivalent capacity \$125 higher per kilowatt generating capacity—1982 dollars. [35] Similar conclusions had been arrived at by the Studies and Evaluation Group of Oak Ridge National Laboratory. [36]

In order for the first LMFBR's to be a commercial success, it would be necessary for their capital cost disadvantage to be made up by savings in fuel costs. The subcommittee heard testimony from Dr. Thomas R. Stauffer, an economist at Harvard University, on this point. [37] Stauffer presented a preview of an analysis of the economics of the LMFBR done by himself, R. S. Palmer (General Electric), and H. L. Wycoff (Commonwealth Edison Co.) for the Breeder Reactor Corp. [38] This analysis calculates the allowable cost capital

differentials between an LMFBFR and an LWR for different prices of uranium oxide ( $U_3O_8$ ). Working in 1975 dollars Stauffer, and others, conclude that, for  $U_3O_8$  cost averaging \$20 per pound over the 30 year lifetime of an LWR, an LMFBFR would be competitive if its capital costs per unit capacity did not exceed those of the LWR by more than approximately \$115 per kilowatt generating capacity. For \$60 per pound  $U_3O_8$  the corresponding capital cost differential went up to approximately \$290. This analysis is generally more favorable to the LMFBFR than a previous analysis [39]—apparently because of different assumptions concerning the discount rates and relative effects of inflation on capital and fuel costs. The average costs of  $U_3O_8$  in 1974 was approximately \$8 per pound. [40] The future price will depend upon the size of the resource base, the rate at which it is consumed and the competitiveness of the market. As has already been noted, ERDA's current estimate is that the U.S. resource of  $U_3O_8$  at prices of less than \$15 forward cost per pound is approximately 2 million tons. [41] This would sustain an LWR capacity large enough to provide all the electric power currently consumed in the United States for over 30 years. [42] If the nuclear sector should grow rapidly beyond this capacity, as is projected by ERDA, then the 2 million tons would be exhausted more quickly.

## VI. LMFBFR PROGRAM MANAGEMENT

The management record of the AEC (now ERDA) in the LMFBFR development program has been plagued by cost overruns, schedule slippages, and other indications of management difficulties. The following notable examples will give the flavor:

The estimated cost of the fast flux test facility has climbed from \$87.5 to \$622 million in 7 years while its capabilities have been reduced and the projected completion date has slipped by 5 years.

The capabilities of the sodium pump test facility were cut back in 1972 when its cost estimates rose from \$6.8 million to \$25.2 million. Now ERDA is redesigning the facility to have increased capabilities again for a total ultimate cost estimated currently at \$57.2.

The Clinch River demonstration breeder reactor was originally supposed to be a demonstration commercial reactor whose costs were to be shared approximately equally by the utilities and the Federal Government. In 3 years the project has slipped by 3 years, the estimated cost has increased by 150 percent to \$1.736 billion, and the Federal Government has assumed all the cost overruns. (See app. G.)

Obviously improvements in the management of the LMFBFR program are called for and changes have been made:

1. In November 1975 the responsible Division of Reactor Research and Development (RRD) was reorganized to have a structure reflecting the various development projects and "to give individual assistant directors more direct authority," [43] over these projects.

2. In 1975 ERDA implemented a new management control system which "is intended to provide increased visibility and better control over RRD programs." [43]

At the same time problems persist in the management of the Clinch River breeder reactor project where the past arrangements have been

termed "complex and potentially cumbersome" by GAO (See app. G.)

## VII. THE ROLE OF THE CLINCH RIVER BREEDER DEMONSTRATION REACTOR AND SUCCEEDING "NEAR COMMERCIAL" BREEDER REACTORS IN ERDA'S LMFBR DEVELOPMENT PROGRAM

The Clinch River demonstration breeder reactor (CRBR) project is currently the focus of ERDA's LMFBR development program. The purpose of this project is not entirely unambiguous, however.

The basic technology of the CRBR is the same as that developed for the fast flux test facility being constructed by ERDA at the Hanford Engineering Laboratory but the CRBR differs from the FFTF in three basic respects:

1. *Scale.*—The thermal power generated by the CRBR will be 975 megawatts versus 400 megawatts for the FFTF and 3,800 megawatts for the commercial LMFBR's projected by ERDA. [44]\* The CRBR therefore represents a stepping stone in the scale-up of the LMFBR technology to commercial size.

2. *The FFTF is not designed to generate electrical power.*—The heat generated by the FFTF will be rejected directly to atmosphere through cooling towers whereas that produced by the CRBR will be used to produce high-pressure steam which will in turn drive a turbo-generator with a full power electrical output of 350 megawatts.\*\* The CRBR therefore requires the development of steam generators in which the heat from molten sodium is transferred to water and converts it into high-pressure steam.

3. *The FFTF is not designed to breed.*—The Clinch River reactor core will be surrounded by rods of depleted uranium oxide taken from the tailings of ERDA's uranium enrichment plants. It is these blanket rods that many of the extra neutrons from the reactor core will convert uranium-238 into uranium-239 which will then be transformed by two successive radioactive decays into plutonium-239. The FFTF will not have this blanket and will consequently, unlike the CRBR, not produce more plutonium than it consumes.

Thus it appears, that, although the basic nuclear technology of the CRBR will be little different from the FFTF, the CRBR will be a complete electrical powerplant which can in principal be scaled up by another factor of four to commercial size.

According to ERDA's LMFBR program review group, the CRBR will:

1. Provide a step in the scale-up of LMFBR technology, and the accompanying scale-up in industrial capability. This will be particularly so for those features outside of the reactor core.
2. Provide a demonstration of LMFBR powerplant operation in a utility environment, and technical information on system per-

\*The power of electrical powerplants is usually given in terms of electrical megawatts. Because the heat generated by the FFTF is dumped to the atmosphere through cooling towers, that is, not converted to electricity; we quote the thermal outputs here. Due to conversion inefficiencies, the electrical output of a powerplant is usually about a factor of three smaller than its thermal output.

\*\*This number is to be compared with the electrical capacities of approximately 1,000 megawatts of light water cooled nuclear powerplants coming on line in 1975 and the electrical capacity of approximately 1,500 megawatts projected by ERDA for early commercial LMFBR's.

formance, safety, fuel performance, reliability, maintainability, and the implications of utility operations.

3. Provide information and training for utilities at all levels of their organization and provide for the infusion of the utilities' expertise into the design, development, and operation of an LMFBR powerplant.

4. Provide information on and experience with the issues associated with licensing a new type of powerplant. [45]

One thing that the CRBR will not prove is that LMFBR's will be economic. According to the analysis of the reactor manufacturer, Westinghouse, as presented by Dr. John J. Taylor, then vice president and general manager of Westinghouse's Advanced Nuclear Systems Division, the cost of the CRBR plant (that is, not including the cost of the associated R. & D. program) in 1974 dollars will be \$832 million, about twice as much as a light-water reactor with three times the electrical generating capacity of the CRBR. Dr. Taylor argued on the basis of Westinghouse analysis, however, that the costs of succeeding plants per kilowatt generating capacity would fall dramatically with increasing size and evolutionary development as has been the case with light-water reactors. [46] During the transition period Federal subsidies would presumably be required.

ERDA has recognized this last fact and envisions in its LMFBR development program one or more federally subsidized "near commercial breeder reactors" (NCBR's) as successors to the CRBR. A GAO report cites:

"ERDA officials (who) told us that in the past under the (LWR) power demonstration plant program, AEC's approach was to provide funds for follow-on plants until their power costs became competitive with then available power sources." [47]

Despite this expectation, ERDA has included only \$300 million in its projected LMFBR development program for subsidies for NCBR's. [48]

As has already been noted, the economics of the LMFBR depend sensitively on the future price of uranium which depends in turn upon the future rate of growth of nuclear power and on U.S. uranium resources—both of which are quite uncertain. In view of these uncertainties, it would be desirable to have a good deal of flexibility in the timing of the LMFBR development program. Unfortunately such a flexibility will become more and more difficult to achieve as the program progresses. Much of the thrust of the LMFBR development program is directed toward developing an industrial capability in those areas of technology unique to the LMFBR. But this capability will not be maintained without orders and orders will not occur if LMFBR's are not built. It will therefore become more and more difficult as the LMFBR program proceeds to postpone the next step toward commercialization—without imperiling the entire LMFBR development program—even if lower electric energy growth rates, larger uranium resources, or high LMFBR capital costs appear to justify postponement of commercialization by a decade or more.

Difficulties of this sort have already been encountered as a result of slippage of the CRBR schedule. In early 1975, the two companies which are fabricating the first two FFTF reactor cores were expected to complete their work by midsummer. Fuel for the CRBR would

not have to be ordered until late 1978. In the absence of other work for ERDA during the interim it appeared that both companies would shut down their facilities and they told GAO that they would probably not reenter the field later when their services were required. ERDA was therefore planning to order two more FFTF cores from one of the companies to tide it over. Even with this strategem ERDA would become dependent on one supplier—a situation which the AEC had assiduously attempted to avoid in the past. [49]



## FOOTNOTES AND REFERENCES

1. See for example: J. Murray Mitchel Jr., "A Reassessment of Atmospheric Pollution as a Cause of Long-Term Changes of Global Temperature," in "The Changing Global Environment," (S. Fred Singer, ed.; D. Riedl Publishing Company, Dordrecht, Holland, 1975 p. 149; Wallace S. Broecker, "Climatic Change: Are We on the Brink of a Pronounced Global Warming?" Science, August 8, 1975, p. 460; Reid A. Bryson, "A Perspective on Climatic Change," Science, May 17, 1974, p. 753.

2. See for example "U.S. Energy Resources a Review as of 1972," background paper prepared for the Senate Committee on Interior and Insular Affairs, 1974 Serial No. 93-40 (92-75), p. 58.

3. See e.g. the testimony of Robert D. Nininger, Assistant Director for Raw Materials of ERDA, "Oversight Hearings on Nuclear Energy—Part II," June 5, 1975, p. 397. Dr. Nininger estimated total U.S. uranium ore resources as 3.6 million tons of  $U_3O_8$ . (This chemical is 85 percent uranium by weight.) In testimony during the same hearing (pp. 404 ff) Milton F. Searl, Manager of the Energy Supply Studies Program of the utilities' Electric Power Research Institute critiqued the methodology used by ERDA at arriving at this estimate and suggested that U.S. uranium resources would ultimately prove to be between 13.2 and 28.9 million tons of  $U_3O_8$  when exploration was carried out to greater depths and to areas of the country not currently producing uranium. Both authors defined high-grade uranium ore as ore containing uranium at a concentration within a factor of three or four of the grade currently being mined. Ore currently being mined averages about two parts uranium per 1,000 parts ore by weight.

4. Recycle of the plutonium would decrease the uranium requirements by about 16 percent (See e.g. "Report of the Liquid Metal Fast Breeder Reactor Program Review Group," ERDA-1, 1975, Attachment 5, p. 17. Tails assay has been assumed to be 0.2 percent.) Recycle of the uranium in the spent fuel would decrease the uranium requirements by an additional 17 percent. (Calculation based information for a pressurized water reactor given in ERDA-1, Attachment 5, p. 17, the "Standard Table of Enriching Services" "AEC Gaseous Diffusion Plant Operations," ORO-684), 1972, p. 37, and a fuel value penalty of 20 percent for recycled uranium due to its contamination by reactor bred  $U^{236}$ . The  $U^{236}$  penalty was based on the calculations of H. O. Sprague, G.E., "Fuel Cycle Effect of  $U^{236}$  in Recycled Uranium," paper presented at the 1974 Annual ANS Meeting at Philadelphia.)

5. See for example, Marvin Resnikoff, "Is Reprocessing Cost Justified?" reprinted in the subcommittee's "Oversight Hearings on Nuclear Energy—Part I," May 2, 1975, p. 857 ff. See also the report by ERDA's Fuel Cycle Task Force, "Nuclear Fuel Cycle," (ERDA-33, March, 1975).

6. Based on the summary descriptions of 1,000 MWe plant concepts presented in the "Proposed Final Environmental Statement on the Liquid Metal Fast Breeder Reactor Program" (WASH-1535, 1974) Vol. II, p. 4.2-165 ff.

7. WASH-1535, pp. 4.7-4 ff.

8. See e.g. the testimony of Theodore B. Taylor, "Oversight Hearings on Nuclear Energy—Part I," May 2, 1975, p. 804 ff.

9. See e.g. Mason Willrich and Theodore B. Taylor, "Nuclear Theft: Risks and Safeguards" (Cambridge, Mass., Ballinger, 1964) chapters 3 and 4.

10. ERDA Press Release, July 24, 1975.

11. Electrical World, September 15, 1975.

12. Based upon: (i) an assumed average load factor of 65 percent (approximately half way between the design capacity factors of about 80 percent and the average capacity factors of about 55 percent currently being realized, (ii) an assumed enrichment which leaves 0.3 percent uranium-235 in the depleted "tails," and (iii) the replacement fuel enrichment, thermal conversion efficiency, and burnup assumed in ERDA-1, "Report of the Liquid Metal Fast Breeder Reactor Program Review Group," Attachment 5, p. 17, 1975.

13. An anticipated shortage of uranium enrichment capacity resulted for a period in ERDA raising content of uranium-235 left in the enrichment "tails" from 0.2 to 0.3 percent. Natural uranium contains 0.71 percent uranium-235.

14. The capacity factor averaged over 40 years assumed in ERDA-I is 56.5 percent compared to our 65 percent over 30 years. On the other hand our calculation neglects the uranium invested in the initial core—approximately 500 tons of  $U_3O_8$  or the equivalent of another 5.5 percent in average load factor over 30 years.

15. Roger Legassie, "Oversight Hearings on Nuclear Energy—Part I," April 28, 1975, p. 142 ff.

16. Robert Smith, "Oversight Hearings on Nuclear Energy—Part I," April 28, 1975, p. 160 ff.

17. John Hill, "Oversight Hearings on Nuclear Energy—Part II," June 2, 1975, p. 53 ff.

18. Duane Chapman and Timothy Mount, "Oversight Hearings on Nuclear Energy—Part II, June 2, 1975, p. 157 ff.

19. John C. Fisher, "Energy Crisis in Perspective" (New York, Wiley, 1974), p. 94.

20. U.S. Department of Commerce, "Statistical Abstract of the United States: 1974."

21. Robert H. Williams, "Oversight Hearings on Nuclear Energy—Part II," June 2, 1975, p. 79 ff. See also the report by Marc H. Ross and Robert H. Williams, "Assessing the Potential for Fuel Conservation," available from the Center for Environmental Studies, Princeton University.

22. Ford Foundation Energy Policy Project, "A Time to Choose." (Cambridge Mass., Ballinger). Appendix F (1974), reprinted in the "Oversight Hearings on Nuclear Energy—Part II," pp. 92-106.

23. John G. Myers, "Energy Conservation and Economic Growth—Are They Incompatible?" "The Conference Board Record," p. 28 ff. (1975), reprinted in the "Oversight Hearings on Nuclear Energy—Part II," pp. 110-115.

24. Robert Nininger, "Oversight Hearings on Nuclear Energy—Part II," June 5, 1975, p. 383 ff.

25. USAEC, "Statistical Data of the Uranium Industry," January 1, 1974 (GJO-100 (74)).

26. Information provided for the record by Robert Nininger, July 14, 1975.

27. WASH-1537, page 6A.1-5.

28. Based on figures in U.S. Department of Interior, "Energy Perspectives," p. 166 (1975).

29. Mr. Milton Searl, "Oversight Hearings on Nuclear Energy—Part II," June 2, 1975, p. 404 ff. and accompanying paper entitled "Views on Uranium and Thorium Resources" by Milton F. Searl and Jeremy Platt, reprinted on pp. 521-534.

30. For details see "Uranium Resources to Meet Long Term Uranium Requirements" (EPRI Special Report #5, November, 1974) reprinted in "Oversight Hearings on Nuclear Energy—Part II," pp. 405-520.

31. *ibid.* p. 49.

32. U.S.G.A.O., "The Liquid Metal Fast Breeder Reactor: Promises and Uncertainties" (1975), p. 39.

33. Alfred M. Perry and Alvin M. Weinberg, "Thermal Breeder Reactors," "Annual Reviews of Nuclear Science 22", 317, (1972).

34. ERDA, "Budget Estimates, Fiscal Year 1976 and Transition Period", Book II, p. NED/F-23.

35. J. J. Taylor, Oversight Hearings on Nuclear Energy—Part II, June 6, 1975, p. 626.

36. WASH-1535, p. 11.2-78 ff.

37. T. R. Stauffer, "Oversight Hearings on Nuclear Energy—Part II", June 5, 1975, p. 560 ff.

38. T. R. Stauffer, R. S. Palmer, H. L. Wycoff, "Breeder Reactor Economics," General Electric, Fast Breeder Reactor Department, Sunnyvale, Calif., 1975.

39. Irvin C. Bupp and Jean-Claude Derian, "Technology Review," July/August 1974, p. 27.

40. AEC, "The Nuclear Industry 1974" (WASH-1174-74), p. 45.

41. Robert D. Nininger "Oversight Hearings on Nuclear Energy—Part II", June 5, 1975, p. 397.

42. It was calculated above that 200,000 megawatts of LWR capacity operated at an average 65 percent load factor with the current "once through" fuel cycle would consume approximately 1.2 million tons of  $U_3O_8$  over 30 years. By returning to previous uranium <sup>235</sup> extraction levels at the enrichment plant (0.2 percent

tails) this requirement could be reduced to approximately 1 million tons. In 1973 the total U.S. electrical capacity was 424,000 megawatts at an approximately 50 percent average load factor. (U.S. Department of Interior, "Energy Perspectives," pp. 70, 80, 1975). In 1974 the electricity consumed stayed approximately constant (Duane Chapman, "Oversight Hearings on Nuclear Energy—Part II," June 2, 1975, p. 158.)

43. GAO, Report to the Congress, "The Liquid Metal Fast Breeder Reactor Program—Past, Present, and Future" (1975), p. 27.

44. Thomas A. Nemzek, "Fiscal year 1976 Authorization Hearings Before the Joint Committee on Atomic Energy," March 11, 1975, Supplementary Information Submitted for the Record, p. 61.

45. ERDA, "Report of the Liquid Fast Metal Breeder Reactor Program Review Group," ERDA-1, (1975), pp. 48, 49.

46. John J. Taylor, "Oversight Hearings on Nuclear Energy—Part II," June 6, 1975, p. 615 ff.

47. GAO, Report to Congress, "The Liquid Metal Fast Breeder Reactor Program—Past, Present, and Future," (1975), p. 24.

48. *ibid.*, p. 11.

49. *ibid.*, pp. 16-18.



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## APPENDIXES

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## APPENDIX A

### THE URANIUM CONSERVATION VALUE OF A BREEDER REACTOR

The heavy elements uranium and thorium contain in their atomic nuclei enormous amounts of stored energy. One pound of any of these elements carries approximately as much releasable energy as 2,000 tons (4 million pounds) of coal.

This energy is releasable by any process which causes the atomic nuclei of these elements to divide or "fission." The process is used in nuclear reactors and nuclear bombs is the "chain reaction," a process in which a neutron released from the fission of one heavy nucleus causes another heavy nucleus to fission and so on.

Only one naturally occurring isotope has been found to sustain such a chain reaction, the rare isotope uranium-235 which makes up 0.7 percent of naturally occurring uranium. The more abundant isotopes uranium-238 (99.3 percent of naturally occurring uranium) and thorium-232 (100 percent of naturally occurring thorium) can be converted into chain reacting isotopes (plutonium-239 and uranium-233 respectively) under neutron bombardment in nuclear reactors, however. For this reason they are called "fertile" isotopes. Current commercial nuclear power reactors are rather inefficient in this conversion process and only convert approximately one fertile atom into a fissile atom for every two chain reacting atoms consumed. The result, is that current reactors can make available approximately equal amounts of energy from the rare uranium-235 isotope and from the much more abundant uranium-238 or thorium-232 isotopes.

In a breeder reactor the ratio of the number of fertile atoms converted to chain reacting atoms per chain reacting atom consumed would be raised above unity, that is it would "breed" more chain reacting atoms than it consumed. The result would be that virtually all of the energy stored in the fertile atoms would become available (aside from a few tenths of percents processing losses) and a pound of uranium or thorium would become in practice the energy equivalent of 1,000 tons of coal.

## APPENDIX B

### ISSUES RELATED TO ENVIRONMENTAL CONTAMINATION BY PLUTONIUM AND OTHER TRANSURANIC ELEMENTS

Plutonium and other "transuranic elements," (most importantly americium and curium) are produced in nuclear reactors by a combination of neutron capture and radioactive transformation. Many of the isotopes of these elements have long lives (plutonium-239, 24,000 years; plutonium-240, 6,600 years; americium-241, 460 years; plutonium-238, 90 years).

The characteristic radiation of the transuranics ("alpha-rays") is so short ranged that it cannot penetrate the skin. These elements therefore do not represent a serious hazard to man when outside the body. They are also not ordinarily absorbed easily through the wall of the gastrointestinal tract when ingested in food. The primary concern therefore is with the consequences of the inhalation of transuranic elements—and, in fact, plutonium has been observed to give lung cancer to experimental animals when inhaled in very small quantities. In an experiment with beagle dogs, for example, virtually all of the animals were found to die from cancer after the inhalation of amounts of plutonium-239 down to approximately 50 billionths of a kilogram of plutonium per kilogram of (bloodless) dog lung.<sup>1</sup> Experiments with lower doses are in progress. Scaling 50 billionths of a kilogram of plutonium-239 per kilogram of lung to an average human lung mass of 0.6 kilograms<sup>2</sup> yields approximately 30 billionths of a kilogram of plutonium-239. On the basis of the dog, other animal experiments, and experiences with the production of lung cancer in humans with other forms of radiation, the environmental impact statement for the LMFBR development program assumes that on the order of this much plutonium-239 inhaled into and retained for a period of a year or two the human lung will result in a cancer.<sup>3</sup> To extend this risk estimates to the estimation of risks for populations, it is ordinarily assumed that approximately the same amount of plutonium distributed between the lungs of a number of persons will result in one lung cancer—even though the risks to the individuals in the population would be reduced as the dose which they received was reduced.

The risk associated by ERDA with plutonium inhalation has been criticized by some scientists who argue that it could be factors of hundreds to hundreds of thousands times higher.<sup>4 5</sup> This is obviously an important dispute and it should be resolved with the utmost urgency.

<sup>1</sup> WASH-1535, p. II.6-57 (1974).

<sup>2</sup> *Ibid.*, p. II.6-34.

<sup>3</sup> *Ibid.*, p. 4.7-15.

<sup>4</sup> *Ibid.*, pp. V.6-1 ff., VI.38-4 ff.

<sup>5</sup> John W. Gofman, *The Cancer Hazard from Inhaled Plutonium* (Committee for Nuclear Responsibility, San Francisco, CNR, 1975-IR, 1975.)

Even if it were possible to determine unequivocally the risk associated with the inhalation of a given amount of plutonium or other radioactive isotopes, it would still be necessary to estimate the probability of receiving such a dose. In the environmental impact statement for the LMFBR development program the AEC estimated an annual release of less than one-millionth of a kilogram of plutonium-239 from the LMFBR fuel cycle per 1,000 megawatt reactor.<sup>6</sup> This corresponds to a release of approximately 1 in a billion of the plutonium atoms flowing through the fuel cycle. With this and correspondingly small releases of the other long-lived transuranic isotopes, ERDA estimated that at most a few persons would die as the result of the inhalation of radioactivity generated from the operation for a year of an LMFBR economy equivalent to 2,200 1,000-megawatt plants postulated for the year 2020.<sup>7</sup>

The containment estimated in the AEC report has been regarded with skepticism in some other quarters. For its own purposes the Environmental Protection Agency has assumed release fractions for plutonium and other transuranic elements up to one-millionth and calculates that in this case the operation of the proposed LMFBR economy in the year 2020 would cause approximately 1,000 extra lung cancer deaths annually.<sup>8</sup> Although undesirable, this would still hardly be considered "catastrophic" in comparison to the approximately 100,000 lung cancer deaths currently occurring annually in the United States. A large increase in this rate would only result for much larger release rates for the transuranic elements or if their carcinogenicity has been grossly underestimated as some scientists have suggested.<sup>4 5 9</sup>

<sup>6</sup> WASH-1535, pp. II.4.7-2 ff. (1974).

<sup>7</sup> Ibid., p. 4-7-17.

<sup>8</sup> EPA, "Environmental Radiation Dose Commitment: An Application to the Nuclear Power Industry" EPA-520/4-73-002 (1974), p. 24.

<sup>9</sup> Karl Z. Morgan, Chairman of the Internal Dose Committees of both the International Commission on Radiological Protection and the National Council on Radiation Protection from 1940 to 1973 has recently proposed that maximum permissible body burdens for plutonium-239 promulgated by these groups be reduced by a factor of 240 based on errors in estimating the radiation doses to critical bone tissues. (Karl Z. Morgan, "Suggested Reduction of Permissible Exposure to Plutonium and Other Transuranium Elements," "Journal of American Industrial Hygiene," August 1975).

## APPENDIX C

### THE RISK OF DIVERSION OF PLUTONIUM TO THE ILLICIT PRODUCTION OF FISSION EXPLOSIVES

On May 2, 1975, Dr. Theodore Taylor, coauthor of the book, "Nuclear Theft: Risks and Safeguards," in testimony to the subcommittee stated that: "Present U.S. physically (sic) security applied to special nuclear materials for civilian purposes, though strengthened substantially during the last two years is still inadequate to prevent theft by determined groups having resources and skills similar to those that have been used for successful bank robbers or hijacking of valuable shipments in the past."<sup>1</sup> He then went on to outline some possibilities for improved safeguards which the Nuclear Regulatory Commission is considering. On the same day Dr. Victor Gilinsky, a member of the Nuclear Regulatory Commission described the current NRC regulations for the safeguarding of plutonium and other "weapons grade" materials. He told the subcommittee that: "We (the NRC) are trying to upgrade the present safeguards system in the most effective way possible."<sup>2</sup> He informed the subcommittee that the NRC is conducting a broad safeguard study<sup>3</sup> on the possibilities as well as a study mandated by Congress on the need of a Security Agency within the Commission.

As has already been noted above, the breeder reactor differs qualitatively from the water-cooled nuclear reactors currently in use in the United States—not in the fact that it produces plutonium but that it requires the recycle of the produced plutonium.

A 1,000 MWe U.S. water-cooled reactor operating at 65 percent average capacity factor produces approximately 200 kg. of plutonium each year.<sup>4</sup> A liquid metal cooled breeder reactor of the same power and with the same average capacity factor would produce between 90 and 250 kg.<sup>5</sup> These figures are quite comparable. The plutonium in water cooled reactors is not (currently at least) being extracted from the spent fuel, however, while the plutonium in the spent fuel from an LMFBR would have to be extracted and recycled within approximately 1 year. This would involve the recycle of approximately 700 kg. of plutonium each year into the breeder reactor.<sup>6</sup> Thus the plutonium processed in the fuel cycle of a single breeder reactor in 1 year would be enough for the fabrication of approximately 100

<sup>1</sup>Theodore B. Taylor, *Oversight Hearings on Nuclear Energy—Part I*, May 2, 1975, p. 806.

<sup>2</sup>Victor Gilinsky, *ibid.*, May 2, 1975, p. 759.

<sup>3</sup>NRC "Special Safeguards Study: Scopes of Work (NUREG-75/060, 1975).

<sup>4</sup>Teknekron, "Fuel Cycles for Electrical Power Generation" (Report to EPA, 1973).

<sup>5</sup>WASH-1537, "Liquid Metal Fast Breeder Reactor Program," IV.B-2. The range corresponds to a breeding ratio of 1.15 for an "early oxide" fueled LMFBR to a breeding ratio of 1.46 for an "advanced carbide" fueled LMFBR with "large diameter pin."

<sup>6</sup>This corresponds to a thermal efficiency of 40 percent, the fission in the core of the equivalent of 75 percent of the plutonium atoms initially loaded into the core and 10 percent of the power coming from fissions of "bred" plutonium outside the core.

fission explosives<sup>7</sup> or, if released into the environment would represent a severe health hazard.

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<sup>7</sup>In his testimony before the subcommittee (ref 2), Dr. Victor Gilinsky, a member of the Nuclear Regulatory Commission stated that, "the minimum quantity of plutonium needed for a comparatively simple nuclear explosive device is about 15 pounds." This corresponds to approximately 7 kg.

## APPENDIX D

### SAFETY ADVANTAGES AND DISADVANTAGES OF THE LMFBR

Relative to water-cooled reactors the LMFBR has both safety advantages and disadvantages.

Among the advantages is the fact that the LMFBR operates well below the boiling temperature of its coolant. This means that, if a pipe were to break, the coolant would not necessarily be lost. In contrast, in the case of a water-cooled reactor much of the superheated water would turn into bubbles of steam which would blow most of the remaining water out of the break.

A principle safety disadvantage of the LMFBR relative to water-cooled reactors is the fact that the chain reaction in an LMFBR does not automatically stop when the coolant starts to boil.

The chain reaction stops in the water-cooled reactor because the chain reacting uranium-235 atoms are so diluted (to the level of 2 to 4 percent) by uranium-238 atoms in the fuel that a neutron must be "moderated" or slowed down by collisions with the hydrogen atoms in water between the fuel rods before it has a good probability of being captured by a uranium-235 nucleus causing it to fission. When the water starts to boil, some of the water is displaced by bubbles, its moderating effect is reduced and the chain reaction dies down.

In contrast, the chain reaction in an LMFBR is propagated by fast "unmoderated" neutron and the fuel has a correspondingly higher ratio (12 to 20 percent) of chain reacting atoms—in this case mostly plutonium-239 and plutonium-241.

These properties of an LMFBR core are intermediate between those of a water-cooled reactor and the core of a fission explosive. Of course, the differences from a fission explosive are still very great: In a fission explosive the enrichment in chain reacting nuclei is above 90 percent and there are no dilutants corresponding to the oxygen in the fuel, the steel structural materials, or the sodium coolant which typically makes up two-thirds of the volume of an LMFBR core. Nevertheless, if a substantial fraction of an LMFBR core were to melt, there is the possibility of a rapid release of a limited amount of nuclear energy. The first burst of energy released would probably be sufficient to disrupt the core structure, but not enough to rupture the reactor pressure vessel. The subsequent development of the meltdown accident is less clearly understood, however. In particular it is important to establish that there will not be later bursts of nuclear energy sufficient to burst the reactor pressure vessel and containment building, opening a path to the human environment for the intense radioactivity in the reactor core. Finally it is important to establish that eventually the molten core will settle down into a form which is sufficiently dispersed so that the chain reaction will stop.

It is interesting to note in this connection that a major sticking point in the discussion between the NRC and ERDA over the licensing of the Clinch River demonstration LMFBR stems from the desire on the part of the NRC staff that a "core catcher" be installed below the reactor core. The purpose of this core catcher would be to catch the core from a meltdown accident and allow it to settle into a stable coolable configuration. The position of the ERDA staff in this discussion is that the control system which inserts neutron absorbing rods in the reactor and thus terminates the chain reaction can be made so reliable that no meltdown accident could possibly occur.<sup>1</sup>

A final safety disadvantage of the LMFBR stems from the fact that the liquid sodium coolant reacts energetically—even explosively—upon contact with air or water. The system must therefore be designed carefully to avoid such contact.

<sup>1</sup> GAO, *"The Liquid Metal Fast Breeder Reactor: Promises and Uncertainties"* (1975), p. 67.

## APPENDIX E

### URANIUM CONSERVING REACTORS INTERMEDIATE BETWEEN LIGHT WATER REACTORS AND THE LIQUID METAL COOLED FAST BREEDER

*Canadian Heavy Water Reactor (CANDU).*—The direction of U.S. commercial power reactor development was substantially influenced by the fact that the United States provided for military purposes during World War II and the years immediately thereafter a large capacity for the enrichment of uranium in uranium-235. This made it possible to develop relatively compact nuclear reactors. Canadian nuclear development was similarly influenced by the construction in that country during World War II of facilities for the production of heavy water. (Heavy water is  $H_2O$  in which the hydrogen has been replaced by heavy hydrogen of deuterium whose abundance in natural hydrogen is only 0.015 percent.)

The advantage of heavy hydrogen for nuclear reactors is that slow neutrons can travel about 16 times as far in heavy water as in ordinary water before being absorbed. This allowed for the Canadians to develop commercial reactors in which the neutron losses to the water were so small that it was possible to use natural unenriched uranium in the fuel.

The Canadian heavy water reactor (CANDU), as currently operated with unenriched uranium fuel, requires the mining of about 20 percent less uranium ore per kilowatt-hour generated than a light water cooled reactor (assuming no recycle of plutonium in either case.<sup>1</sup> By slightly enriching the uranium in the CANDU the savings could be increased to about 40 percent. The relative advantage of the CANDU with unenriched uranium fuel would be increased still further with plutonium and uranium recycle in both reactor types—to about a factor of two.

*Thorium Fuel Cycle.*—By introducing a new element, thorium, into the fuel of many types of reactors, even greater conservation of uranium resources can be achieved. The slowed down neutrons which are used in U.S. light water, Canadian heavy water, and U.S. high-temperature, gas-cooled reactors are more effective in converting fertile thorium-232 into chain reacting uranium-233 than they are in converting uranium-238 into chain reacting plutonium-239. The high-temperature gas-cooled reactor (HTGR) developed by General Atomic Co. in the United States is in fact fueled with almost pure uranium-235 and thorium. With recycle of the bred uranium-233 it would consume approximately 30 percent less uranium than the light-water reactor. With fuel changes approximately twice as frequent as

<sup>1</sup> The references for the uranium utilization figures used in this discussion are as follows: light water reactor and HTGR—ERDA-1, Attachment 5, page 17; CANDU—J. S. Foster and E. Crltoph, "The Status of the Canadian Nuclear Power Program and Possible Future Strategies," discussion paper presented for the Wingspread Conference on Advanced Nuclear Converters and Near Breeders, May 14-16, 1975.

currently considered economically optimal, the saving with the HTGR could be increased to over 60 percent. The advantages of using the CANDU on the uranium-thorium fuel cycle with uranium-233 recycle are similar: approximately 70 percent savings relative to the light-water reactors operating with uranium and plutonium recycle.

## APPENDIX F

### FACTORS BEARING ON THE CAPITAL COST DIFFERENCES BETWEEN LIGHT-WATER COOLED AND LIQUID METAL COOLED BREEDER REACTORS

Many of the factors which bear on the relative capital costs of the LMFBR and of current U.S. reactors stem from the fact that the LMFBR uses a liquid metal as a coolant while most current U.S. reactors use ordinary light water.

The use of a liquid metal as a breeder reactor coolant stems from the stringent demands which breeding puts on the neutron economy of the reactor. Upon fissioning a chain reacting nucleus releases on the average between two and three neutrons. One of these neutrons on the average must cause the fission of another nucleus so as to continue the chain reaction. In order for breeding to occur, that is in order to get a net increase in the amount of chain reacting material in the reactor, it is necessary for at least one of the remaining neutrons to convert a fertile nucleus into a new chain reacting nucleus. Thus, on the average, at least two of the neutrons released in a fission process have to be utilized profitably in a breeder reactor and, since less than three are released in the first place very little wastage of neutrons can be allowed.

One of the ways in which the neutron economy of a breeder reactor is optimized is by adjusting the speed of the neutrons causing the fissions so that the maximum number of neutrons are released per neutron captured in the chain reacting fuel. For a breeder based on the fission of plutonium, as is the LMFBR, this ratio is maximized when the neutrons lose as little energy as possible between their emission and absorption. The reactor must be designed, therefore, so that: (1) a neutron in the chain reaction should bounce off as few atoms as possible between the fission event which produces it and that which it causes in turn, and (2) the neutron loses as little energy as possible in each collision that it does undergo.

Both of these conditions are met using a liquid metal coolant: (1) such a coolant is much more effective than water in removing heat from the surfaces of the fuel—consequently the fuel rods can be packed closer together in the coolant and a neutron going from one fuel rod to another has to penetrate fewer coolant atoms. (2) The light neutron will lose much less energy in a collision with a heavy metal atom because that atom—unlike the light hydrogen atom in water—will hardly recoil at all. Molten sodium has been selected as the coolant for the LMFBR.

Sodium has both economic advantages and disadvantages relative to water as a coolant. Its advantages stem primarily from its high boiling point, 1,620°F. One consequence is that it is possible to operate the reactor at low pressure—unlike water-cooled reactors where the water is kept at very high pressures (up to 2,500 pounds per square inch) so that it may be superheated to temperatures where conversion of heat into electrical energy is relatively efficient. With a low-pressure

system the tanks and pipes which constitute the reactor plumbing can be designed with thinner walls and quality standards are less critical to public safety.

Another advantage of the high boiling point of sodium is that it becomes possible to operate the reactor at higher temperatures than water-cooled reactors which operate at between 500 and 600°F. LMFBFR's would probably heat their sodium coolant to temperatures of the order of 1,000°F which would give them a thermal conversion efficiency of about 40 percent—considerably higher than the 33 percent being achieved by water-cooled reactors. The higher thermal efficiency of the LMFBFR would result in cost savings because a smaller turbine, less cooling water, smaller cooling towers et cetera are required per unit power output as the thermal efficiency increases.

The economic disadvantages of sodium as a coolant stem primarily from it having the unfortunate property of burning vigorously—even explosively—if it comes into contact with air or water. As a result, elaborate arrangements are required when loading or unloading the fuel in the reactor or performing other required maintenance operations to insure that air does not obtain access to the sodium. Since the LMFBFR is designed to have a steam driven turbine-generator system for converting the heat in the sodium to electrical energy, great care is also required to prevent leakage between the sodium and water sides of the steam generators. In the current designs the heat is transferred first from the radioactive sodium which cools the reactor to nonradioactive sodium and then to the water. In this way, if a sodium-water fire should occur, at least it won't involve the highly radioactive primary coolant.

There is some question as to whether the economic advantages would outweigh the disadvantages of sodium as a coolant over the long term. The balance will be determined in part by whether it is decided in the future that current designs are overly conservative in, for example, the degree of separation between the steam generator and the primary sodium. In the short term, however, it appears clear that the capital costs for the LMFBFR would be higher than those for water-cooled reactors.

## APPENDIX G

### SOME MANAGEMENT PROBLEMS IN THE LMFBR DEVELOPMENT PROGRAM AS DOCUMENTED IN GAO REPORTS

*Fast flux test facility.*—The FFTF is a nuclear reactor being built at ERDA's Hanford Engineering Development Laboratory in Washington State. In many ways it is the precursor of the demonstration breeder reactor which ERDA plans to build on the Clinch River in Tennessee—whose design is in fact in good part based on that of the FFTF. The FFTF will be a reactor with about 40 percent of the thermal power of the Clinch River reactor designed to test the properties of breeder fuel and materials under LMFBR operating conditions.<sup>1</sup> According to a 1975 GAO review of the FFTF program:

AEC's initial cost estimate (\$87.5 million) at project authorization was based upon several contractor-prepared conceptual design cost studies. In December 1968, AEC approved a changed core concept . . . The initial estimate was dependent upon the use of several components already proven in a sodium reactor environment. Because off-the-shelf items were not available, however, AEC subsequently was required to establish or reestablish an industrial capacity for manufacture of components of (sic) high temperature sodium service and to develop new nuclear industry standards for these new higher temperatures.

Several major components and facilities included in the conceptual design studies were deferred or deleted from the project and numerous consolidations and simplifications were made . . .

In July 1970 AEC presented to the Joint Committee a start of construction capital cost estimate of \$102.8 million . . .

On January 29, 1973, AEC advised the Joint Committee it was increasing the construction cost estimate from \$102.8 to \$187.8 million . . .

In a letter of April 4, 1973 to AEC's general manager, the Joint Committee's Executive Director stated that the total costs associated with construction of the FFTF appear significantly greater than those which were included in the budget data on the construction project. He was also of the opinion that the Commission had not fully and promptly advised the committee of the changing cost estimates, schedule delays and other factors.

AEC was then requested by the Joint Committee to provide a current estimate of all costs associated with the FFTF, including those in the operating budget, as well as any plant and equipment obligations . . .

On May 17, 1973, for the first time AEC provided the Joint Committee with a cost estimate in one place for the entire FFTF program—\$509 million . . .<sup>2</sup>

On March 11, 1975, Thomas A. Nemzek, ERDA's Director, Division of Reactor Research and Development, told the Joint Committee:

A change is not being proposed in the official ERDA estimate of FFTF project cost—\$530 million . . . at this time. However the project is experiencing substantial inflationary growth . . . On the basis of these current trends, the project is forecasting a project cost of \$622 million . . .<sup>3</sup>

The GAO review commented on the lateness of previous cost estimate increases as follows:

<sup>1</sup> Thomas A. Nemzek, Director, Division of Reactor Research and Development, ERDA, information supplementary to testimony before the Joint Committee on Atomic Energy, March 11, 1975, pp. 54, 61.

<sup>2</sup> GAO Staff Study, "Fast Flux Facility Program," 1975, pp. 11-14.

<sup>3</sup> Ref. 1, p. 57.

From June 1970 until January 1973, AEC's plant and capital equipment estimate held at \$102.8 million. On January 29, 1973, at which time costs totaling about 83 percent of the \$102.8 million estimate were incurred or committed, AEC told the Joint Committee that it was increasing the FFTF estimate to \$187.9 million . . .

In November 1973, at the request of the AEC Chairman, AEC and FFTF contractor officials developed a revised plant and capital equipment cost estimate for the project which amounted to \$420 million . . . As in the case of the previous increase, funds equivalent to a major portion of the existing estimate (76 percent) had been incurred or committed.<sup>4</sup>

The GAO review also noted that:

The FFTF has experienced a substantial schedule slippage. In March 1967, shortly before authorization of the FFTF projects, AEC informed the Joint Committee that FFTF construction was expected to start by June 1968, and that full power operation would begin early in 1974. Because of considerable delays in the conceptual and preliminary design effort, however, FFTF construction did not actually start until July 1970—a slippage of about 2 years, AEC headquarters officials informed us that achievement of the full power operation milestone is not now expected until May 1979.

At start of FFTF construction, only limited detailed design effort had been accomplished and, since that time, design and construction have been accomplished concurrently.<sup>5</sup>

Despite the increase in estimated costs by a factor of 7 and slippage of the full power operation date by 5 years, the current design is less flexible than that originally conceived and the GAO has expressed concern that "these changes may limit the number and type of experiments that can be performed" at the FFTF.<sup>6</sup>

*Sodium pump test facility.*—A precedent exists in another LMFBR development program project for GAO's concerns about the ability of the redesigned FFTF to accomplish its mission. According to another GAO report:

The construction of the sodium pump test facility was authorized in the fiscal year 1966 budget. The estimate presented to Congress for approval at that time was \$6.8 million. In 1969, a review of the project by a private architect-engineering firm revealed that the project, with its then current scope, would cost \$25.2 million.

To reduce estimated costs, the project scope was then revised to test sodium pumps having a capacity of about one-third the size of those initially anticipated to be tested. The reduced project scope resulted in a cost estimate of \$12.5 million for the facility. This estimate was presented to and approved by the Congress as part of AEC's fiscal year 1972 budget request. In fiscal year 1974, this \$12.5 million estimate was again revised up to \$17.5 million. At that time, AEC stated that the reduced capability of the facility would not adversely affect the capability to test pumps up to the sizes needed for use in the foreseeable future of the LMFBR program.

ERDA is presently planning modifications to this facility so it can test CRBR (Clinch River breeder reactor)—size pumps, which are larger than the pumps for which the facility is presently designed. These modifications are presently estimated to cost \$40 million, increasing the project's total cost to \$57.5 million.<sup>7</sup>

To test full size plant components with sodium, ERDA has recently added to the LMFBR program a plant component test facility which is currently estimated to cost about \$200 million and is planned for operation in the early 1980's.<sup>8</sup>

<sup>4</sup> Ref. 2, pp. 17, 18.

<sup>5</sup> Ref. 2, p. 19.

<sup>6</sup> Ref. 2, p. 22.

<sup>7</sup> GAO Report to the Congress, "The Liquid Metal Fast Breeder Program—Past, Present, and Future," pp. 25–26.

<sup>8</sup> Ref. 7, p. 21.

*Clinch River breeder reactor.*—The CRBR is supposed to be a demonstration commercial breeder reactor generating about one-quarter to one-third the power of the full sized LMFBFR's<sup>9</sup> the first of which ERDA expects to have operating in 1987.<sup>10</sup>

The CRBR is a joint government-industry effort. In August 1972:

AEC estimated that \$699 million would be required to design, construct, and operate the project, of which private project participants, primarily utilities were expected to provide from \$274 to \$294 million including \$20 to \$40 million from reactor manufacturers. AEC was authorized to contribute a total of about \$422 million, \$92 million of which was to be in direct financial assistance, \$10 million in special nuclear materials, and \$320 million in development work from AEC's ongoing LMFBFR base program. Base program funds were limited to 50 percent of the then estimated capital cost of the plant. The direct assistance and base program funds were restricted as to what they could be used for. In general, they could not be used for end capital items for the plant.

ERDA's cost estimate for completing the CRBR project is now \$1.736 billion—an increase of more than \$1 billion. Because utility contributions were fixed, ERDA, by contract, accepted the open-end financial risks connected with the project and agreed to seek funds for any cost increase...<sup>11</sup>

The date for commercial operation of the CRBR has slipped by 3 years in 3 years—to early 1983. According to a GAO report, additional delays may be expected:

Two important project milestones are (1) obtaining a limited work authorization by September 1, 1975, and (2) obtaining a construction permit by August 1, 1976.

Delays have already occurred in the licensing process. According to ERDA, neither the limited work authorization milestone nor the construction permit milestone will be met. A delay of 4 months could be expected in each category...

The application for a limited work authorization was submitted to NRC (Nuclear Regulatory Commission) in October 1974. NRC, however, has not formally accepted the application for docketing because it feels additional information is necessary before a complete review of the application is possible...<sup>12</sup>

The GAO report goes on to describe other potential future causes of delay in the CRBR project: lack of timely and adequate funding, public hearings and outside legal interventions during the licensing process, delays in the delivery of long leadtime material and components, unavailability of craftsmen—particularly welders, and potential design changes—in particular those relating to a "core catcher" which is favored by the NRC but not by ERDA.<sup>13</sup>

Due to the joint industry—ERDA funding of the CRBR project, a Project Management Corporation was established directed by a three-man steering committee representing ERDA, the Tennessee Valley Authority, and Commonwealth Edison. (The Tennessee Valley Authority is providing the site, will operate the plant, will purchase the power it produces, and will have the option to buy it after the project is over. Commonwealth Edison is providing engineering management and purchasing services for the project.) The GAO has described the organizational arrangement for the project as "complex and potentially cumbersome."<sup>14</sup>

<sup>9</sup> Ref. 1, p. 61.

<sup>10</sup> GAO Issue Paper to Congress: "The Liquid Metal Fast Breeder Reactor: Promises and Uncertainties" (1975), p. 101.

<sup>11</sup> GAO, Report to the Joint Committee on Atomic Energy, "Comments on Energy Research and Development Administration's Proposed Arrangement for the Clinch River Breeder Reactor Demonstration Project" (1975).

<sup>12</sup> GAO, Report to the Congress, "Cost and Schedule Estimates for the Nation's First Liquid Metal Fast Breeder Reactor Demonstration Power Plant" 1975, p. 27.

<sup>13</sup> Ref. 12, pp. 27–33.

<sup>14</sup> Ref. 7, p. 31.



With the increase in ERDA's participation from approximately 60 percent, when the management arrangement was established, to 85 percent with the new cost estimates. ERDA on March 10, 1975, proposed to the Joint Committee on Atomic Energy new management arrangements which "are necessary to clearly delineate the manner in which the project will be managed in the future, in recognition of the major increase in governmental financial involvement and the need to establish a single-line integrated project management organization."<sup>15</sup> The GAO has reviewed the proposed changes, however, and concluded that:

In our opinion, the various documents submitted to the Joint Committee do not clearly delineate the manner in which the project will be managed, but rather contain ambiguous and seemingly inconsistent language regarding responsibilities and authorization and management.<sup>16</sup>

In particular the proposed new arrangements would leave the Project Management Corporation (PMC) to manage the project subject to being overridden by ERDA. PMC in its role as representative of the utilities, however, would have the right to disapprove "any proposed major changes in Project Scope or deviation from the approved reference design or specifications." If PMC were to disagree with such changes, the utilities could terminate their involvement with the project. The GAO comments that:

Such inconsistencies suggest to us that ERDA will not be able to exercise the usual management prerogatives in the areas of design and other changes and that it may be subject to restraints in other management areas.<sup>17</sup>

The GAO report continues:

We discussed these inconsistencies with ERDA officials and they told us that, although they believe the documents are clear, ERDA will revise the documents to state that ERDA will manage the project. ERDA officials stated also that the revised four-party contract would clearly state that ERDA would manage the project.<sup>17</sup>

<sup>15</sup> Letter from ERDA to the Joint Committee quoted in ref. 11, p. 4.

<sup>16</sup> Ibid., p. 4.

<sup>17</sup> Ibid., p. 6.

